Deep Water Ocean Acoustics (DWOA): The Philippine Sea, OBSANP, and THAAW Experiments

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LONG-TERM GOALS

A wealth of novel data on deep-water acoustic propagation and ambient noise has been collected in a wide variety of environments over the last few years with ONR support, enabled in part by the development at SIO of a Distributed Vertical Line Array (DVLA) receiver. The DVLA makes feasible large-aperture vertical receiving arrays that were heretofore difficult or impossible to deploy (Worcester *et al.*, 2009). The experiments include the (1) NPAL Philippine Sea experiments, (2) 2013 Ocean Bottom Seismometer Augmentation in the North Pacific (OBSANP) experiment, and (3) 2013 THin-ice Arctic Acoustic Window (THAAW) experiment. All of these experiments are intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, and (ii) the structure of the ambient noise field in deep water at low frequencies. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

Philippine Sea. During 2009–2011 three experiments were conducted to study deep-water acoustic propagation and ambient noise in the oceanographically and geologically complex northern Philippine Sea: (i) 2009 NPAL Pilot Study/Engineering Test (PhilSea09), (ii) 2010–2011 NPAL Philippine Sea Experiment (PhilSea10), and (iii) Ocean Bottom Seismometer Augmentation of the 2010–2011 NPAL Philippine Sea Experiment (OBSAPS) (Worcester *et al*., 2013).

The goals of the Philippine Sea experiments included (i) understanding the impacts of fronts, eddies, and internal tides on acoustic propagation, (ii) determining whether acoustic methods, together with other measurements and ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improving our understanding of the physics of scattering by internal waves and spice (density-compensated temperature and salinity variations), (iv) characterizing the depth dependence and temporal variability of the ambient noise field, and (v) understanding the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals.

OBSANP. The 2013 OBSANP experiment was conducted to study (1) the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals transmitted by a J15-3 source and (2) the relationship between deep ocean ambient noise and sea surface processes that generate sound (Stephen *et al*., 2014). The experiment was motivated in part by unexpected arrivals (named Deep Sea-Floor (DSF) arrivals) observed on OBSs at 5000-m depth in the Northeast Pacific Ocean from broadband signals transmitted by a 75-Hz source during the 2004 Long-range Ocean Acoustic Propagation Experiment (LOAPEX) (Stephen *et al.*, 2009, 2013).

THAAW. The 2013 THAAW experiment was a preliminary effort by SAIC, SIO, and WHOI to test the hypothesis put forward by P. Mikhalevsky (pers. comm.) that changing Arctic conditions will contribute to a THin-ice Arctic Acoustic Window (THAAW):

- The Arctic is now dominated by 1–2 year ice with reduced pressure ridging, resulting in lower transmission loss and allowing operation at higher frequencies.
- Reduced pressure ridging also results in more frequent periods of low ambient noise.
- Ice cover is still present throughout much of the year, insulating the ocean from wind and solar forcing and preserving the stable Arctic acoustic channel.

The goals with the ambient noise data collected as the DVLA receiver deployed by SIO and WHOI near the North Pole in April 2013 drifted south toward Fram Strait are to characterize the ambient noise and assess its relationship to the ice cover, atmospheric and other forcing, and to the ocean sound-speed field.

APPROACH

Philippine Sea. The three NPAL Philippine Sea experiments are described in detail in Worcester *et al*. (2013). The PhilSea09 experiment was a short-term Pilot Study/Engineering Test during which a single acoustic path was instrumented with a Teledyne Webb Research (TWR) swept-frequency source and a prototype DVLA receiver. The PhilSea10 experiment embedded a water-column-spanning DVLA with 150 Hydrophone Modules within an ocean acoustic tomography array that provided data to help characterize this oceanographically complex and highly dynamic region. The DVLA recorded ambient noise and the transmissions from the six TWR transceivers that made up the tomographic array in order to study acoustic propagation and scattering. A DVLA with 15 Hydrophone Modules extending up 1000 m from the seafloor and an array of six ocean bottom seismometers (OBSs) were deployed during April-May 2011 for the OBSAPS experiment (Stephen *et al*., 2011). The instruments recorded transmissions from J15-3 source suspended from shipboard as well as the background ambient noise.

OBSANP. A DVLA with 32 Hydrophone Modules extending up 1000 m from the seafloor and an array of twelve OBSs were deployed during June-July 2013 at the location in the Northeast Pacific Ocean at which Deep Sea-Floor arrivals were first observed on OBSs during the 2004 LOAPEX experiment (Stephen *et al*., 2014). The instruments recorded transmissions from a J15-3 source suspended from shipboard as well as the background ambient noise. Two of the OBSs had ultra-low-noise hydrophones developed by SAIC in order to ensure that the low-frequency ambient noise measurements would not be limited by the hydrophone self-noise.

THAAW. In mid-April 2013 a Distributed Vertical Line Array (DVLA) with 22 hydrophone modules distributed over a 600-m aperture immediately below the subsurface float was moored near the North Pole. The top ten hydrophones were spaced 14.5 m apart. The distances between the remaining hydrophones increased geometrically with depth. Temperature and salinity were measured by thermistors in the hydrophone modules and ten Sea-Bird MicroCATs (J. Colosi, NPS). The mooring parted just above the anchor shortly after deployment and subsequently drifted slowly south toward Fram Strait until it was recovered in mid-September 2013. The DVLA recorded low-frequency ambient noise (1953.125 samples per second) for 108 minutes a day, six days per week.

WORK COMPLETED

Philippine Sea. A number of papers analyzing data collected in the Philippine Sea experiments are in press (Van Uffelen *et al*., 2015) or have been submitted (Andrew *et al*., 2015; Gopalakrishnan *et al*., 2015; Ramp *et al*., 2015). Our colleagues at other institutions took the lead in preparing Andrew *et al*. (2015), Ramp *et al*. (2015), and Van Uffelen *et al*. (2015). SIO's principal focus over the past year has been on using the Philippine Sea data (both acoustic and non-acoustic) to constrain a high-resoluiton regional implementation of the MIT ocean general circulation model (MITgcm). Gopalakrishnan *et al*. (2015) used the MITgcm and its adjoint (the Four-Dimensional Variational (4DVAR) method) to match the model fields to non-acoustic data (satellite sea-surface height and sea-surface temperature observations; temperature and salinity profiles from Argo) by adjusting model temperature and salinity initial conditions, open boundary conditions and atmospheric forcing fields over assimilation windows of one or two months. Ocean state estimates that incorporate the travel times in addition to the non-acoustic data have now been completed.

OBSANP. A paper analyzing seafloor ambient noise data collected during the passage of a cold front across the OBSANP array has been submitted (Farrell *et al*., 2015).

THAAW. Analysis of the ambient noise data collected as the DVLA drifted south from near the North Pole toward Fram Strait has continued. Previous efforts examined the statistics of the entire data set. During this fiscal year, time periods during which the subsurface float was on the surface (so that the location was known) and strumming of the mooring appeared minimal have been analyzed and the results presented at national and international conferences.

RESULTS

Philippine Sea. The ocean state estimates that resulted from constraining the high-resolution MITgcm with non-acoustic data showed many interacting cyclonic and anti-cyclonic eddies moving primarily westward in the domain (Gopalakrishnan *et al*., 2015). The modeled eddies have high relative vorticities ($> 0.1f$), surface currents up to 1 ms^{-1}, and are strongly interacting. It is somewhat of a surprise that the linearized 4DVAR method works in this eddy-active region over the two-month assimilation windows. The large scale of the eddies allowed the use of increased viscosity in the adjoint to quell the nonlinearity while retaining the larger-scale gradients needed to fit the observations satisfactorily. The observed low-frequency travel-time series compare remarkably well with time series computed from the ocean state estimate constrained by non-acoustic data. The similarities cross-validate the state estimates, while the differences (~ 30 ms) provide a simple estimate of the novel information present in the travel times.

The ocean state estimates were then re-computed to fit the acoustic travel times as integrals of the sound speed, and therefore temperature and salinity, along the ray paths. Over the approximately one-year experiment, the state estimate was able to match the travel times within their error bars while not significantly increasing the misfits with the other observations (Fig. 1). Comparisons of the state estimates with and without the travel-time data showed significant changes to the temperature and salinity were made to fit the acoustic observations. The state estimates using the acoustic data compare favorably with independent observations.

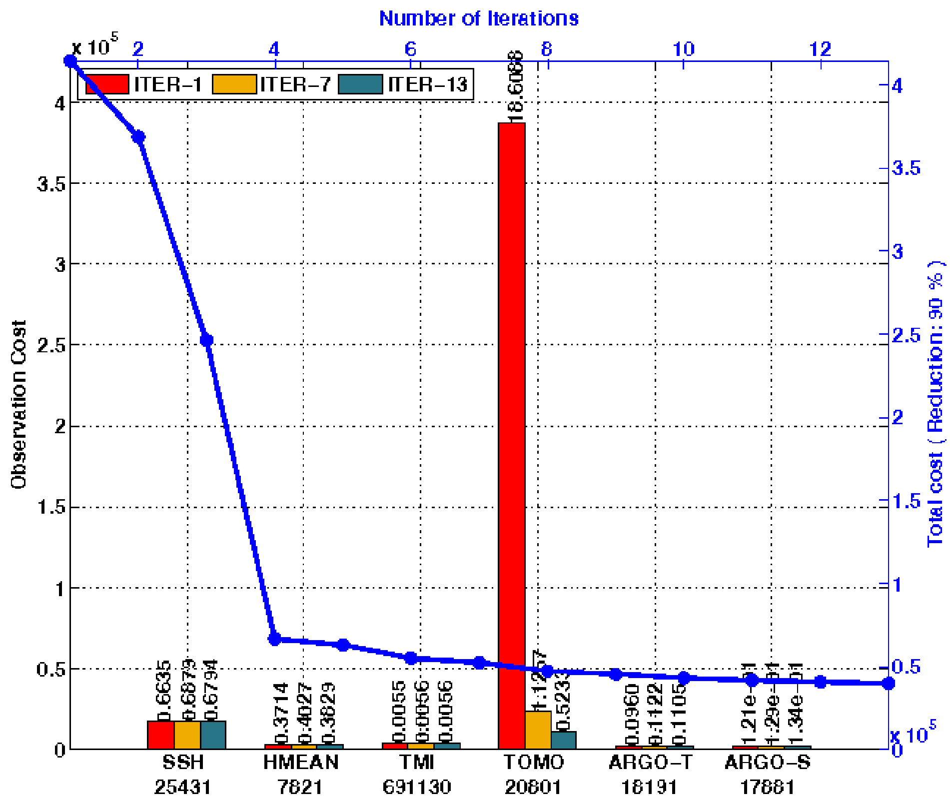

Fig. 1. The misfit (observation cost) for the acoustic travel times (TOMO) decreased dramatically as a function of the iteration number when the MITgcm state estimate was constrained to match the travel times in addition to the non-acoustic data (sea-surface height, SSH: mean geoid, HMEAN; sea-surface temperature, TMI; Argo temperature profiles, ARGO-T; Argo salinity profiles, ARGO-S). The misfits for the non-acoustic observations were initially small (because the initial state of the MITgcm had been previously constrained to fit these data) and remained so.

OBSANP. A quick and broadband (1 hr, $1 < f < 400$ Hz) increase in pressure and vertical velocity on the deep ocean floor was observed on seven OBSs comprising a 20 km array in the Northeast Pacific Ocean as a cold front passed over (Farrell *et al*., 2015) (Fig. 2). The 4-Hz spectra are consistent with Longuet-Higgins radiation as the source physics (Farrell and Munk, 2010). The jump in the spectra at 400 Hz occurs about 25 minutes later than at 4 Hz. The implications of this difference for the source physics at 400 Hz are uncertain (Farrell and Munk, 2013).

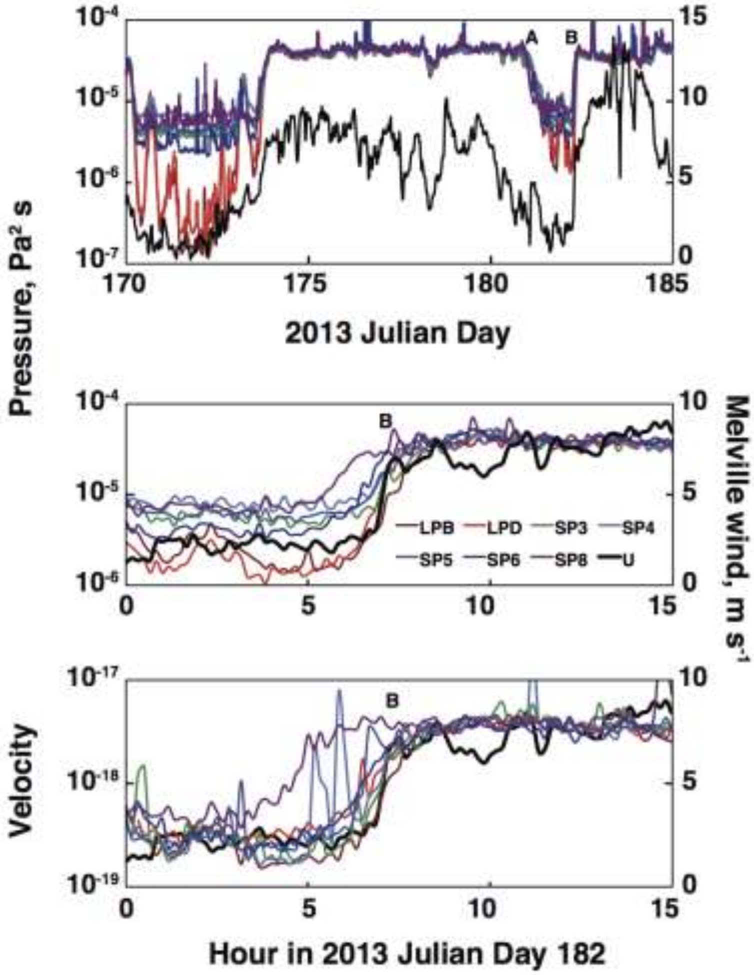

Fig. 2. The 4 Hz spectral estimates of pressure (top) measured by OBSs during the OBSANP experiment are nearly independent of wind in the middle week when the wind speed rarely dropped below 6 ms^{-1}. This span is bracketed by busts. The spectra have been equalized to obtain superposition during the intervals with high winds. For the hours surrounding time B, the spectra of pressure (middle) and vertical velocity (bottom, units (ms^{-1})^2 s) show the acoustic jump varies with location and is more gradual than the jump in the wind. The legend in the middle panel shows the color coding for the seven OBS stations. The wind in top panel is smoothed over 1 hour and in the others over 10 minutes.

THAAW. Previously reported noise levels in the Arctic are highly variable, with periods of low noise when the wind is low and the ice is stable and periods of high noise associated with pressure ridging. The median noise level at 98 m depth measured during the first two weeks of May not far from the North Pole had a maximum between 10 and 20 Hz of approximately 75 dB re 1 μPa^2/Hz, which is very roughly 10 dB less than observed during the FRAM IV ice camp somewhat further south in April 1982. During this time the median ambient noise levels increased with depth by roughly 2–3 dB between 100 and 600 m. The background noise levels are at times extraordinarily low, with the 10th percentile over a 108-minute period limited by the self-noise of the hydrophones (35 and 26 dB re 1 μPa^2/Hz at 100 and 1000 Hz, respectively) above approximately 100 Hz. These levels are below the lower limit of prevailing noise on the Wenz curves.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior.

RELATED PROJECTS

The NPAL Philippine Sea experiments involved a large number of institutions and investigators: APL-UW (R. Andrew, B. Dushaw, A. Ganse, F. Henyey, J. Mercer, A. White), George Mason University (K. Wage), MIT (A. Baggeroer), NPS (J. Colosi, K. Raghukumar), NPS/IIT-Madras (T. Chandraydula), OASIS (R. Campbell, K. Heaney), SIO-UCSD (B. Cornuelle, G. D'Spain, M. Dzieciuch, W. Munk, P. Worcester), Soliton Ocean Services (S. Ramp), University of Hawaii (B. Howe, B. Powell, L. Van Uffelen), University of Miami (M. Brown), WHOI (J. Kemp, R. Stephen), and WHOI/Raytheon (I. Udovydchenkov). The OBSANP project was a joint effort by SIO-UCSD (M. Dzieciuch, P. Worcester) and WHOI (R. Stephen). W. Farrell has participated in the data analysis. The THAAW project was a joint effort by SIO-UCSD (M. Dzieciuch, P. Worcester), WHOI (J. Kemp), and NPS (J. Colosi). It was designed to augment the SAIC (P. Mikhalevsky) THin-ice Arctic Acoustic Window (THAAW) project, which was one component of the DARPA Assured Arctic Awareness program.

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